CHAPTER

40

Silage Production

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Ensiling

Across the world, ensiling is a growing practice for preserving forages (Wilkinson and Toivonen, 2003). Such a trend suggests that ensiling is a relatively recent practice. However, there is evidence that crops have been preserved by ensiling for at least 3000 yr (McDonald et al., 1991; Woolford, 1984). Murals in Egypt, dating from 1000 to 1500 B.C., suggest that whole-plant cereal crops were preserved using ensiling. Silos dating from 1200 B.C. have been found in the ruins of Carthage. In addition, various early manuscripts in the Mediterranean area note the importance of sealing the crop for good preservation.

Ensiling appears to have been a relatively localized phenomenon until the 1800s. Grieswald in 1842 published the first recommendations for making fresh grass silage (McDonald et al., 1991). His recommendations are still recognized as important: filling the silo rapidly, packing the crop well, and effectively sealing out air. In 1877, Goffart, a French farmer, published the first book on ensiling, detailing his experiences in making whole-plant corn silage. About a year later, an English translation was published in the United States, stirring great interest in ensiling corn in North America. Ensiling was also furthered by the invention of the tower silo by F.H. King in Wisconsin in 1889 (Woolford, 1984). By the 1900s ensiling was a common, although not dominant, means of preserving crops in both Europe and North America.

Preservation Mechanisms

Ensiling uses two primary mechanisms to preserve a moist crop: an anaerobic environment and a fermentation of plant sugars to lactic acid producing a low pH. An anaerobic environment is essential to prevent the growth of aerobic spoilage microorganisms (including molds, yeasts, and bacteria) because many of these microorganisms can grow at low pH (<4.0) but require oxygen. Thus the sealing of a silo is critical to achieving and maintaining an anaerobic environment. Any oxygen remaining in the silo after sealing is usually used up by plant respiration within a few hours.

A low pH reduces the activity of plant enzymes and inhibits growth of undesirable anaerobic bacteria. Inhibition of clostridial bacteria is most critical to successful silage preservation. These bacteria produce butyric acid and amines from fermentation of sugars or lactic acid and amino acids, respectively. Such fermentations cause losses of dry matter (DM) and reduce silage intake by ruminants.

Generally, lactic acid bacteria (LAB) already present on the crop produce the low pH by fermenting plant sugars, primarily producing lactic acid, as well as acetic acid, ethanol, and other products. Beyond lowering pH, the lactic and acetic acids at sufficient levels are themselves inhibitory to undesirable aerobic bacteria and fungi, respectively. Natural fermentation can be assisted by inoculating the crop with selected LAB or by adding an acid to immediately reduce pH.

Importance of Ensiling

Farmers have two options for storing forages: ensiling or haymaking. The predominant means in a region varies by climate and, to some extent, by tradition, technology available, and use. In haymaking, the largest losses occur during harvesting, with little loss during storage if the crop is sufficiently dry. In ensiling, harvest losses are reduced, but storage losses increase. Hay is more mar-

Table 40.1. Estimated production of silage and hay in selected countries in 2000

		Silage		
Country	Hay	Grass	Corn	Other
		(million Mg DM)		
Australia	4.5	0.9	0.3	0.04
Austria	1.9	1.6	1.2	0.2
Belgium	0.9	1.1	2.4	na
Bulgaria	1.8	na*	0.3	0.1
Canada	45.0	na	2.8	4.8
Chile	0.6	1.3	na	na
Czech Republic	1.7	7.3	2.6	0.5
Denmark	0.07	0.8	0.6	0.8
Finland	0.6	1.8	na	0.02
France	22.5	6.1	16.8	5.3
Germany	2.0	8.6	14.6	3.2
Ireland	1.0	5.1	0.04	na
Italy	15.1	0.2	6.9	0.4
Japan	1.5	2.2	1.1	0.07
New Zealand	0.4	0.6	0.3	0.02
Norway	0.08	2.3	na	0.1
Poland	8.6	2.1	2.2	2.6
Slovakia	0.8	1.8	0.6	1.0
South Africa	1.5	0.3	1.9	0.8
Spain	3.1	1.7	0.7	0.2
Sweden	0.4	3.6	0.03	0.02
Switzerland	1.7	0.3	0.4	na
The Netherlands	0.3	4.3	2.9	0.07
Turkey	1.5	na	0.8	0.1
United Kingdom	2.5	9.4	1.1	0.4
United States	138.0	1.7	32.4	9.0

Source: Adapted from Wilkinson and Toivonen, 2003.
*na = Estimate not available.

ketable than silage, whereas the handling of silage is more easily mechanized. Countries with predominantly dry climates, such as the United States and Australia, preserve most of their forage as hay (Table 40.1). In contrast, most northern European countries store forages as silage due to their wet climates.

In many countries it appears that silage production is increasing relative to hay (Wilkinson and Toivonen, 2003). In western Europe, silage was approximately 40% of harvested forage production in 1975, whereas today it accounts for 67%. In the United States, silage- (largely corn silage) to-hay ratios have remained constant, but legume silage production increased approximately 50% between 1984 and 2000 (Wilkinson and Toivonen, 2003).

Success in ensiling crops depends on five general areas: the crop, harvest management, silo type, silo management, and silage additives.

Crop Factors Influencing Ensiling

Chemical Composition

Certain crops, such as whole-crop corn, have a reputation as being easy to ensile. In contrast, alfalfa is generally viewed as being difficult to ensile. Three characteristics of a crop may explain such perceptions: nonstructural carbohydrates, buffering capacity, and moisture content.

Nonstructural Carbohydrates

The crop provides the substrates, primarily sugars, that the LAB ferment to produce lactic acid and other products. Glucose is the most universally fermented sugar by the various species of LAB found on plants. However, all common plant monosaccharides and disaccharides can be fermented by at least some strains of LAB. Also, some plant organic acids such as citric and malic may be fermented.

The LAB found on forage plants generally are not able to ferment larger oligosaccharides or polysaccharides such as cellulose and hemicellulose and the storage carbohydrate starch. One exception is fructan, the storage carbohydrate in cool-season grasses. Recent research suggests that bacteria play a role in fructan hydrolysis during ensiling, and three effective *Lactobacillus* strains have been isolated (Merry et al., 1995; Winters et al., 1998). However, most LAB isolated lacked this ability.

Even if LAB cannot directly use plant polysaccharides, some polysaccharides are hydrolyzed by plant enzymes during ensiling, producing monosaccharides and disaccharides that can be fermented. The most common sources are the nonstructural polysaccharides, starch and fructan, that are hydrolyzed by plant amylases and fructan hydrolases, respectively.

Buffering Capacity

The crop also contains compounds that resist pH decline. This resistance is called *buffering capacity*. The most common definition of buffering capacity is the meq H^+ kg^{-1} crop DM needed to decrease pH from 6.0, the typical crop pH at ensiling, to 4.0, the final pH required for an anaerobically stable, unwilted cool-season grass silage. Unfortunately, this is not a universal definition. Typical variants are the milliequivalents of lactic acid required to reach pH 4.0 and/or the milliequivalents of acid starting from the actual crop pH at ensiling, not pH 6.0.

The buffering capacity is attributed primarily to salts of various anions such as organic acids (e.g., citric, malic, malonic), phosphates, sulfates, nitrates, and chlorides. Some amino acids also cause buffering in this pH range (Playne and McDonald, 1966). In general, forages with higher mineral contents have higher buffering capacities.

Moisture Content

The moisture content of the crop at ensiling affects the rate and extent of fermentation. A drier crop has a higher concentration of solutes dissolved in the residual plant moisture, raising osmotic pressure. Higher osmotic pressure reduces microbial growth rate, raises the critical pH that is inhibitory to microbial growth, and thus reduces the quantity of sugar needed to be fermented for an anaerobically stable silage. Beyond fermentation effects, crops ensiled too wet may produce effluent. Crops ensiled too dry are more prone to heating and spoilage.

Species Differences

The type of crop, crop maturity, and environmental factors affect the buffering capacity and amount of sugar at harvest. Silage crops are divided into five general groups: annual and perennial C_3 (cool-season) grasses, annual and perennial C_4 (warm-season) grasses, and legumes. Perennial grasses and legumes are generally ensiled at vegetative to boot or early bloom stages. Silages from annual cool-season grasses such as wheat, oat, and barley can be harvested at those maturities but are more often ensiled later, between the boot and milk stages. Silages from annual warm-season grasses such as corn and sorghum are harvested normally in the milk stage.

Buffering capacities vary considerably within and across species (Table 40.2). Legumes tend to be highest. Cool-season and warm-season grasses often have similar ranges.

Buffering capacity declines with maturity in silage crops (Muck and Walgenbach, 1985; Muck et al., 1991). The sources of buffering (salts and amino acids) are diluted by the increasing levels of insoluble components (e.g., cell wall, insoluble seed carbohydrates) as the plant matures. This suggests that annual grasses, which are harvested at later reproductive stages, should require less sugar for successful fermentations than the perennial grasses and legumes, which are harvested at more vegetative stages.

Buffering capacity is also affected by soil fertility and moisture stress. High fertility increases mineral uptake and buffering capacity whereas moisture stress decreases buffering capacity (Melvin, 1965; Playne and McDonald, 1966; Muck and Walgenbach, 1985).

Cool-season grasses are highest in soluble sugars, and warm-season grasses tend to be lowest (Table 40.3). However, reported values vary widely, depending on species and environmental conditions around the time of harvest. In addition, fructan in cool-season grasses is often hydrolyzed to a greater extent than starch in legumes and warm-season grasses during harvesting and ensiling. In part this may be due to LAB fermenting fructan.

Maturity effects on sugar levels of forage crops are inconsistent. Leading up to the full-bloom stage for legume crops, water-soluble carbohydrate (WSC) concentrations tend to decline with time (Smith, 1973). In contrast, WSC concentrations in cool-season grasses increase with advancing maturity (McDonald et al., 1991). In whole-crop cereals (both cool- and warm-season), WSC concentrations increase until the milk stage of seed development and then decrease as the seed develop (Fig. 40.1).

Environmental factors also affect shoot WSC concentrations. High soil fertility and shade reduce WSC concentrations, whereas drought has the opposite effect (Buxton and Fales, 1994). Concentrations of WSC vary diurnally, being highest in late afternoon and lowest in early morning.

Whole-crop cereals are ideal crops for ensiling due to

Table 40.2. Buffering capacities of various forage species

Species	Number of samples	Buffering capacity (*meq kg*$^{-1}$ *DM*) Range	Mean
Cool-season grass[1]			
Timothy	2	188–342	265
Orchardgrass	5	247–424	335
Italian ryegrass	11	265–589	366
Perennial ryegrass	13	257–558	380
Warm-season grass[2]			
Corn	39	148–351	260
Sweet sorghum	18	176–430	297
Sorghum × sudangrass	16	333–571	458
Pennisetum millet	6	315–520	393
Kikuyugrass	11	269–496	388
Legume[1]			
Alfalfa	9	390–570	472

[1]McDonald et al., 1991.
[2]Kaiser and Piltz, 2002.

Table 40.3. Typical concentrations of nonstructural carbohydrates in perennial forages

Category	Temperate legumes	Cool-season grasses	Warm-season grasses
		(*g kg*$^{-1}$ DM)	
Soluble sugars	20–50	30–60	10–50
Starch	10–110	0–20	10–50
Fructan	–*	30–100	–

Source: Adapted from Moore and Hatfield, 1994.
*Not present in significant quantities.

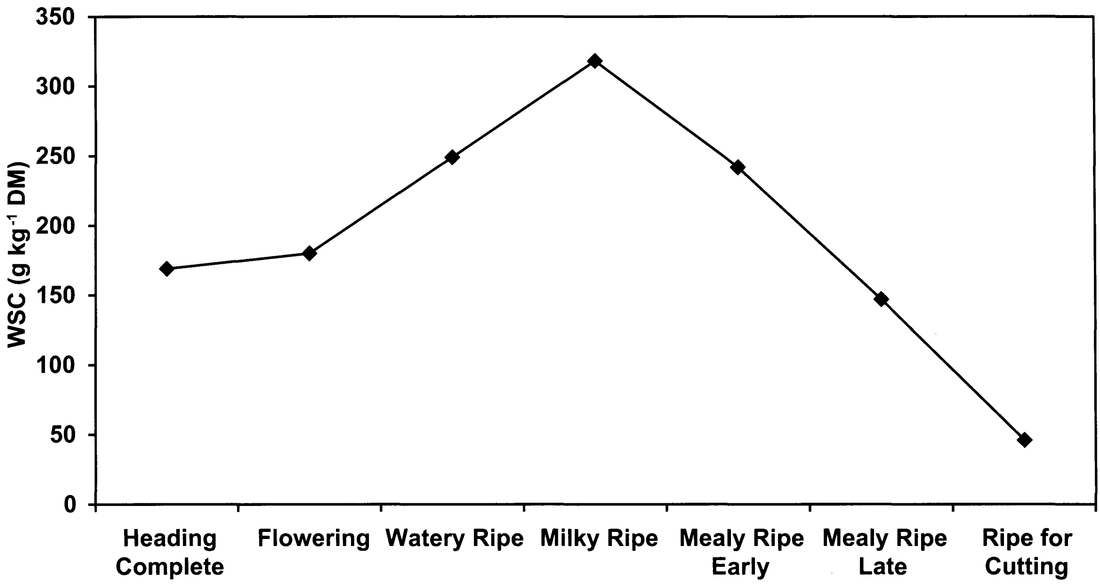

FIG. 40.1. Average WSC content in four cultivars of whole barley plants at different stages of maturity. (Adapted from Edwards et al., 1968.)

high WSC and low buffering capacities and generally attain silages with pHs at or below 4.0. Among perennial forages, cool-season grasses are easiest to ensile, and their ease of preservation as silage increases as they mature due to increasing WSC levels and decreasing buffering capacity. Compared with cool-season grasses, generally lower WSC concentrations make warm-season perennial grasses more difficult to ensile. High buffering capacities and low WSC concentrations make legume crops the most difficult to ensile. Because sugar concentrations and buffering capacity both decline with maturity, ease of preservation of legume silage changes little with crop maturity.

While such generalizations are useful, perennial forages are usually harvested when the moisture concentrations in the standing crop are high (800–900 g kg^{-1}). If ensiled at these moisture concentrations, even perennial cool-season grasses are susceptible to clostridial fermentation if sugar concentrations are too low. Where 1- or 2-d windows occur frequently for field drying, perennial forages are typically mown, wilted in the field to 750 g moisture kg^{-1} or less, and then chopped and ensiled. In tropical areas where daily showers occur and in cool, damp climates as found in northern Europe, farmers often ensile perennial forages with little or no wilting. Under these conditions, monitoring of sugar content to ensure it is high enough and using silage additives may be necessary to minimize clostridial activity.

Harvesting Issues

Moisture

Moisture concentration profoundly affects fermentation and subsequent nutritive value of silage because of the effects on microbial growth. In standing forage, lack of metabolizable nutrients (e.g., WSC) and dry plant surfaces prevent the growth of microorganisms that are naturally found on the crop. However, chopping releases nutrients and moisture that encourage microorganisms to multiply. Assuming that forage has been packed tightly and quickly to remove air, LAB on these surfaces use the moisture and WSC for growth and produce lactic acid and other products.

In forages dried to below 650 g moisture kg^{-1} (or >350 g DM kg^{-1}) before chopping, LAB become stressed, and the rate and amount of lactic acid production are decreased (Fig. 40.2). When moisture concentration is below 200–300 g kg^{-1}, bacterial-growth is completely inhibited. The net effect is that drier silages ferment less of the available sugar, form fewer fermentation products, and have higher pH values (Fig. 40.3).

Conversely, excess moisture (>700 g kg^{-1}), while stimulating growth of LAB, also encourages the growth of some undesirable bacteria. Clostridia in particular thrive in wet conditions and can dominate the ensiling process in grasses and alfalfa, resulting in a low-quality product. The pH that must be achieved to avoid significant

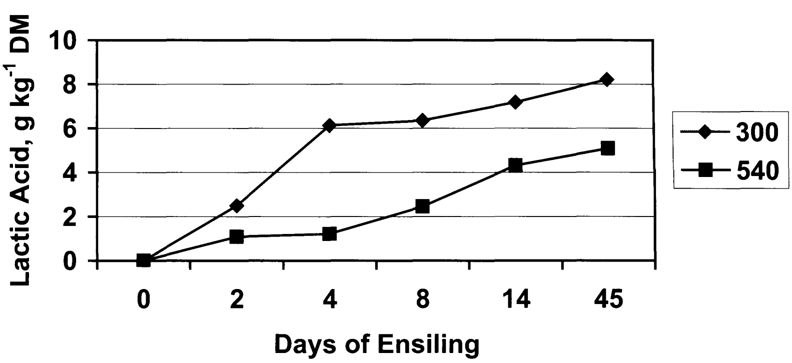

Fig. 40.2. Lactic acid production in alfalfa ensiled at two moisture contents. (Adapted from Whiter and Kung, 2001.)

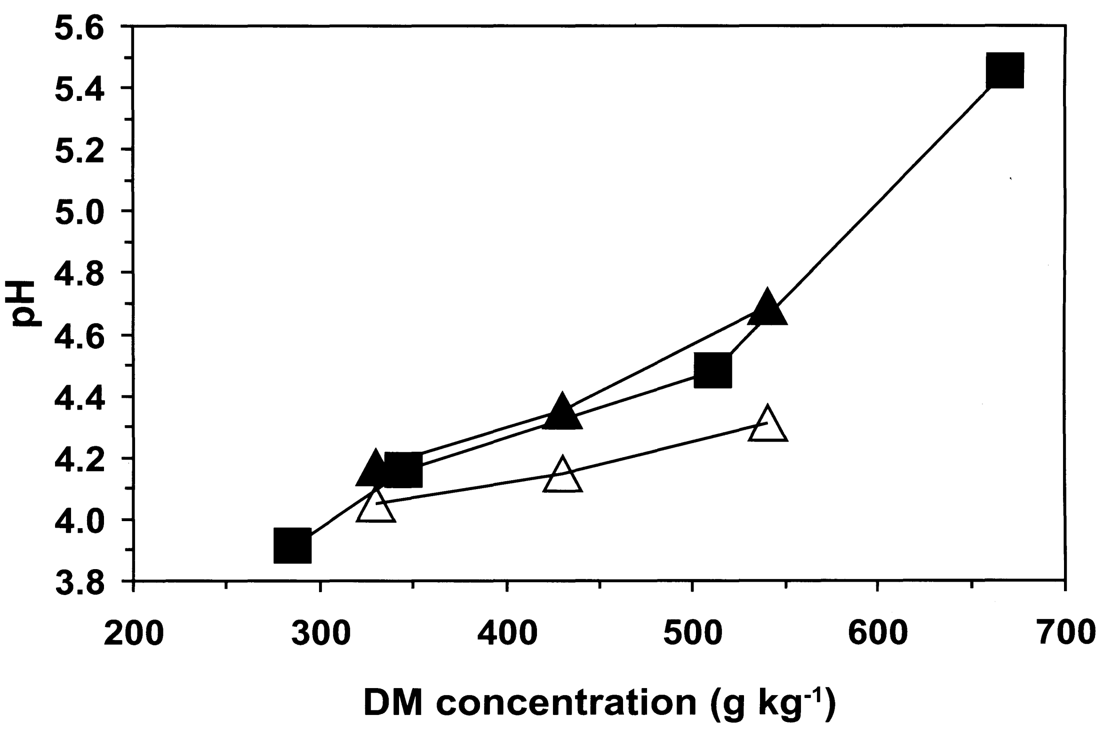

Fig 40.3. Final pH of alfalfa ensiled over a range of moisture concentrations with additional glucose to promote a fermentation ended by low pH. (Data from Muck, 1987 *[squares],* and Jones et al., 1992 *[triangles].*)

clostridial growth is lower for wetter silage (Fig. 40.4). Thus, because corn silage readily ferments to pHs below 4.0, clostridial activity is rare. In contrast, the high buffering capacity and low sugar concentration in alfalfa typically require wilting the crop to less than 700 g moisture kg^{-1} to inhibit clostridial growth.

High moisture concentrations are also undesirable because compaction in the silo may produce seepage (efflu-

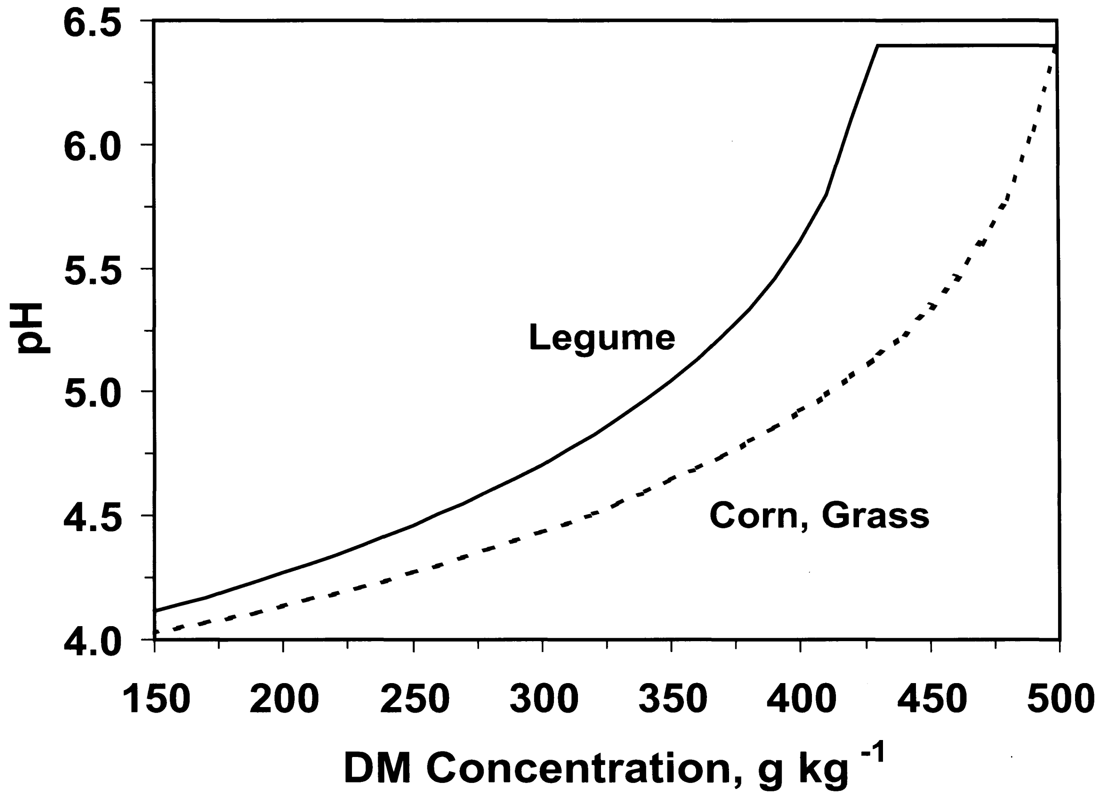

FIG. 40.4. The pH below which the growth of *Clostridium tyrobutyricum* ceases as a function of the moisture concentration of the ensiled crop. (Based on Leibensperger and Pitt, 1987.)

ent) losses, which contain high levels of soluble nutrients. Silage effluents are as environmentally damaging to surface waters as manure slurries. The moisture concentration needed to avoid effluent varies by silo structure, ranging from less than 700 g moisture kg^{-1} for bunker and pressed bag silos to less than 550 g kg^{-1} for large tower silos.

Silage porosity, that is, fraction of gas voids, is inversely related to its moisture concentration. More porous silages are more susceptible to spoilage by aerobic microorganisms when oxygen is present at filling and emptying or if the silo is not sealed well. The growth of aerobic microbes is accompanied by significant heat production. More heat is required to raise the temperature of water in plant matter than of gasses or plant DM, so the temperature of a wet silage is raised less than that of a dry silage for a given amount of heat production. High temperatures (>35°C) reduce silage quality by stimulating the Maillard reaction in which amino acids are bound to carbohydrates. Excessive heating binds these amino acids irreversibly and thus decreases the availability of protein to the animal. Recommended minimum moisture concentrations for different silo types take potential spoilage and heating problems into account.

Length of Cut

The optimal particle or chop length for ensiled forage is a compromise between longer particles to meet the requirement for "effective fiber" by the animal and the need for short particles that pack well and exclude air from the silo. Lactating dairy cows need effective fiber that stimulates cud chewing and production of saliva. Saliva contains large quantities of buffers that help maintain optimum rumen pH for fiber-digesting bacteria. Chop-length settings of 10–13 mm (3/8–1/2 in.) for unprocessed corn and legume silages and 19 mm (3/4 inch) for kernel-processed corn silage have been suggested (Shaver, 1993, 2003). Even longer particles would theoretically further increase saliva production, but these particles would pack poorly, especially when moisture content is below 600 g kg^{-1}. For very dry silages, a shorter chop length may be warranted to ensure good packing and adequate silage density.

Kernel Processing

The protective pericarp of intact corn kernels must be broken to provide access for rumen microbes and digestive enzymes that digest kernel starch. The addition of a kernel processor to a forage harvester accomplishes this task. In this process, the chopped particles are passed between two rollers set 1- to 3-mm apart that break the kernels. Well-processed corn silage should have at least 95% of its kernels broken, and the cob should be broken into six or more small pieces.

Predicted improvement in starch digestion in dairy cows due to processing corn silage increases as whole-plant moisture concentration decreases as the kernel matures (Schwab et al., 2003). If whole-plant moisture exceeds 700 g kg^{-1}, processing will probably have minimal benefits and could increase seepage. Processing effects on fiber digestion have been inconsistent. Improvements in milk production from processing have been observed in some studies (Bal et al., 2000) but not in others (Weiss and Wyatt, 2000), probably due to variation in the stage of corn maturity, amount of starch in the diet, stage of lactation, and forage particle size. Processing corn silage has also improved pack density and aerobic stability (Johnson et al., 2002).

FIG. 40.5. Typical bunker silo covered with polyethylene and used tires.

FIG. 40.6. Pressed bag silo.

Silo Types

Drive-over Piles, Bunker Silos

Common methods for silage production range from low-cost covered piles to permanent concrete or steel structures.

The most common silos worldwide are piles placed on the ground, concrete pad, or asphalt and covered with polyethylene plastic. A variant of this is the bunker silo with walls on two or three sides (Fig. 40.5). Crops are commonly ensiled at 600–700 g moisture kg^{-1} in these silos. Ensiling at higher moistures than these is common in northern Europe and in tropical areas but require facilities to collect and dispose of effluent.

The capital cost of pile silos is low, needing only plastic to seal out air. However, the large surface area increases the risk of significant spoilage losses compared with those in more permanent structures where a concrete or steel wall reduces air contact.

Losses are minimized by decreasing crop porosity, maintaining the integrity of the plastic seal, and removing silage from the face during feedout at high rates. Porosity is inversely correlated to the density and moisture concentration of the crop. Density in these types of silos is highly variable (approximately 100–400 kg DM m^{-3}) (Muck and Holmes, 2000) and is determined by how the crop is packed during filling. Porosity is decreased by spreading each load thinly over the silo surface, using a heavy tractor for packing, increasing the depth of silage, and increasing packing time per unit wet weight.

The plastic must adhere tightly to the crop to minimize storage losses. In North America, used tires are common, but sand, soil, and a wide variety of other materials can be used to weight the plastic and create a tight seal. When the surface is left uncovered, spoilage losses of 40% or more occur in the top 50-cm layer of silage (Bolsen et al., 1993).

Pressed Bag Silos

Use of pressed bags, another type of horizontal silo, is increasing in North America because of the low cost, variable capacity, and the ability to segregate silages by quality (Fig. 40.6). Bags may be placed on bare ground, but unloading of bags in wet regions is easier if the bags are located on concrete or asphalt.

FIG. 40.7. Bagging machine showing the inlet to the bags.

There are a wide variety of bagging machines and bag sizes. Nominal bag diameters are 1.8–3.6 m, and standard lengths are 30, 60, and 90 m. Bags are filled through a slot in the bagging machine by a set of rotating fingers (Fig. 40.7). Both tractor-powered and self-propelled bagging machines are available. The bagging machine is pushed forward as the bag is filled. Silage density in the bag is regulated by varying the force needed to push the machine forward using external cable tension between the front and back of the bag, tractor brakes, and/or internal chains or cables.

The goal in filling the bag is to obtain a dense but smooth bag surface surrounding the finished product. Excessive density can lead to an irregular surface on the filled bag, creating passageways for air to move back rapidly from the open face. This exposes more of the silage to oxygen soon after opening, increasing the opportunity for spoilage and heating.

This silo type can produce an excellent fermentation because the crop becomes anaerobic rapidly, is protected from rainfall during filling, and should maintain the seal from oxygen exposure during storage. However, the polyethylene is the only seal and is susceptible to puncturing by birds, animals, and hail. Also the surface-to-volume ratio is higher than for bunker or pile silos. Consequently, monitoring and patching plastic is more critical than for other horizontal silos.

Tower Silos

Tower silos come in three common types: concrete stave (Fig. 40.8), poured concrete, and oxygen-limiting steel (Fig. 40.9). Although these are more costly to build than other silo types, they are more permanent and are present on more than half of all dairy farms in the United States (Anonymous, 2002).

Filling is accomplished by blowing the crop into the top of the silo. In concrete stave silos, the unloader, located at the top of the silo, blows silage through doors located in the side of the silo and down a chute (Fig. 40.8). In oxygen-limiting steel silos, the unloader is at the bottom of the silo. Poured concrete silos may be set up for either type of unloading mechanism.

FIG. 40.8. Concrete stave tower silos showing blower pipes for filling on the left side of each silo and the unloading chute for the left silo.

The weight of the crop being ensiled compacts material beneath it in the silo and produces the final silage density. Smaller-diameter silos have lower densities because of the greater relative contribution of wall friction. Taller silos achieve higher densities than shorter silos. Densities at the bottom of tower silos are such that the crop needs to be less than 600 or 650 g moisture kg^{-1} to avoid effluent production.

The upper surface of upright concrete silos is usually left open to the air. Spoilage may affect a 1-m depth of this loose material, and it is commonly discarded when emptying begins. The walls of older silos may need to be

FIG. 40.9. Oxygen-limiting steel tower silos.

relined or the seals on doors fixed if substantial spoilage is evident. In oxygen-limiting silos, a breather bag at the top of the silo prevents oxygen from entering the silage under normal storage conditions while permitting gases in the silo to expand and contract due to diurnal heating and cooling. As this type of silo is emptied from the bottom, the silage slides down and some air enters the silo, equal to the volume of silage removed.

Wrapped Bales

The wrapping of large, round or rectangular bales with multiple layers of stretch polyethylene film is becoming more popular as an ensiling practice. It is most prevalent in Europe (Anonymous, 2002; Wilkinson and Toivonen, 2003). Bales may be wrapped individually (Fig. 40.10) or wrapped in lines end-to-end. Also in a process similar to bag silage, round bales may be placed end-to-end in a bag.

These systems have many of the same advantages and

FIG. 40.10. Wrapping of individual large, round bales with stretch polyethylene film to make silage. (Courtesy of K.J. Shinners.)

disadvantages of pressed bag silage. Additional benefits include (1) allowing a farmer to make hay under good conditions and silage when rainy conditions prevail, and (2) allowing silage to be bought, sold, and transported as individually wrapped bales.

Management of the plastic is essential for good preservation. A minimum of four layers of 25-μm stretch polyethylene film is needed. More is desirable for long storage periods or in warm climates to maintain plastic integrity and minimize losses in these conditions. Like pressed bag silage, monitoring for and patching holes is critical to minimize spoilage.

The long forage particles in wrapped bales do not ferment as well as chopped forage in other systems. Some balers have stationary knives to cut forage in 40- to 100-mm lengths, depending on the model, which should improve fermentation. Even so, wilting legumes such as alfalfa to 600 g moisture kg^{-1} or less is recommended to avoid clostridial fermentation.

Losses

Tower silos, particularly oxygen-limiting silos, are the most consistent at preserving the crop with low DM losses (Table 40.4). Wrapped bales and bag silos can produce similar results when plastic is maintained without holes. Pile and bunker silos usually are sealed less effectively than wrapped bales and bag silos so losses are typically higher, but the reduced surface-to-volume ratio of these bigger silos prevents the catastrophic losses that can occur in bags and wrapped bales.

Storage/Feeding Management Issues

Losses during storage consist of fermentation losses and microbial respiration of oxygen entering the silo. Fermentation losses (typically 1%–4%) are considered unavoidable and are primarily the result of CO_2 production during fermentation of hexoses to acetic acid or ethanol. However, such losses can be reduced by bacterial

Table 40.4. Recommended DM concentrations for ensiling and typical DM losses for different silo types

Silo type	Recommended DM range	Typical range of DM losses	Expected DM loss, good management
	($g\ kg^{-1}$)	*(%)*	*(%)*
Drive-over pile	300–400	10–35	15
Bunker silo	300–400	8–30	12
Pressed bag	300–400	3–40	10
Concrete stave tower	350–450	5–15	10
Oxygen-limiting tower	450–550	3–12	6
Wrapped bale, individual	400–700	3–40	8
Wrapped bale, line	400–700	3–40	10

inoculants as discussed later. The most significant losses during storage and emptying are losses from aerobic microbial respiration. Minimizing a silage's exposure to oxygen minimizes respiration losses. Prior to opening the silo, seal integrity and silage porosity affect respiration losses. During the emptying process, silage porosity, feedout rate, and feedout surface influence respiration losses.

Seal Integrity

Silos are not hermetically sealed, so some movement of oxygen into silos during storage is unavoidable. Diurnal heating and cooling cause pressure differences that expel gases from a silo during the day and draw air in at night. Wind passing over a silo creates a pressure differential between the windward and leeward sides of a silo that draws air into the silo. Also if a plastic cover is not held tightly to the silage, the wind may cause it to act like a bellows pumping air into a silo. Polyethylene and concrete allow a slow diffusion of oxygen. After active fermentation in the silo, the gas atmosphere in silage may be 900 mL L^{-1} or more CO_2. Because CO_2 is heavier in air, it moves downward to the bottom, where it may exit if openings allow, thus pulling outside air into the top. One or more of these factors will cause a slow continuation of respiration losses in even the best-sealed silos.

Holes in plastic sheeting or cracks in silo walls allow oxygen to penetrate at a rate that is proportional to the area of the hole, the porosity of silage near the hole, and duration of the exposure. Porosity is a function of density and DM concentration of the silage (Fig. 40.11). In all silo types, ensiling forage that is too dry leads to increased porosity and thus susceptibility to spoilage losses. In pile, bunker, and bag silos, packing management also determines density and subsequent effects on respiration losses when holes occur.

Feedout Rate

When the silo is opened, oxygen is present at the open face and diffuses into the silage from the face. In bunker silos with above average densities, measurable oxygen concentrations have been observed 1 m back from the face in several studies (Honig, 1991; Weinberg and Ashbell, 1994). Typical feedout recommendations in the northern United States for bunker silos are 15 cm d^{-1}. At that rate, silage would be exposed to oxygen for almost 1 wk prior to removal. While gas measurements have not been made in other silo types, recommended feedout rates are inversely proportional to the average density among silo types. This suggests that 7 or more days of oxygen exposure are typical prior to feeding in all silo types except for individually wrapped bales that are used when opened.

The effect of the feedout rate on respiration losses in silage near the face has not been measured directly. Modeling of microbial respiration at the silo face indicates a nonlinear relationship between losses and feedout rate (Fig. 40.12). This suggests that substantial losses can occur during silo emptying when feedout rates are low. Much circumstantial evidence indicates that low feedout rates lead to heating and excessive spoilage of silages.

Feedout Surface

Tower silos are emptied with specialized unloaders that leave a smooth feedout face. This is not necessarily the case with pile, bunker, or bag silos. In North America, front-mounted buckets on tractors, skid-steers, or industrial loaders are used most frequently to unload these silos. This creates a ragged face and may open seams for more rapid oxygen ingress from the open face.

Various specialized bunker silo unloaders are commercially available: block cutters, milling devices, grab buckets, etc. A milling device was found to reduce the surface area on the face of a bunker silo by 9% in corn silage and 26% in alfalfa silage compared with that on a well-managed skid-steer face (Muck and Huhnke, 1995). This device also reduced oxygen concentration in the silage behind the face (up to 1 m) by 12–22 mL L^{-1} compared with a conventional bucket unloader. The effect in alfalfa was greater than in corn silage because the greater propor-

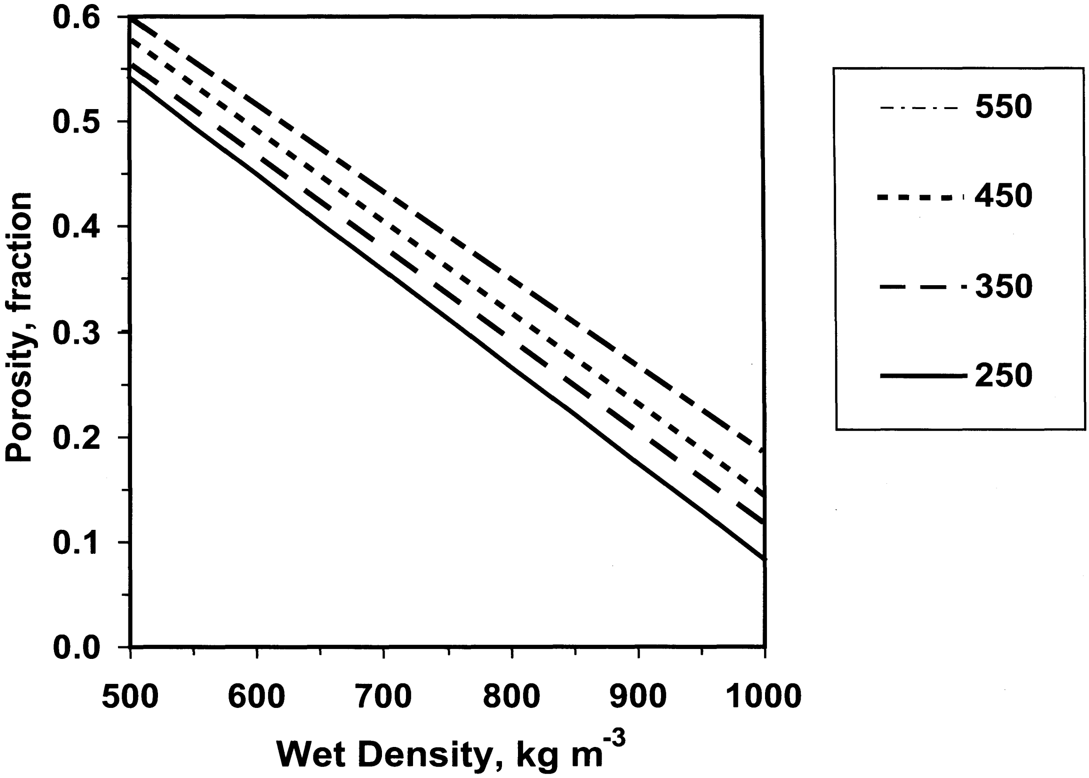

FIG. 40.11. Porosity in silage as a function of density and DM concentration (250, 350, 450, and 550 g kg^{-1}) of the silage.

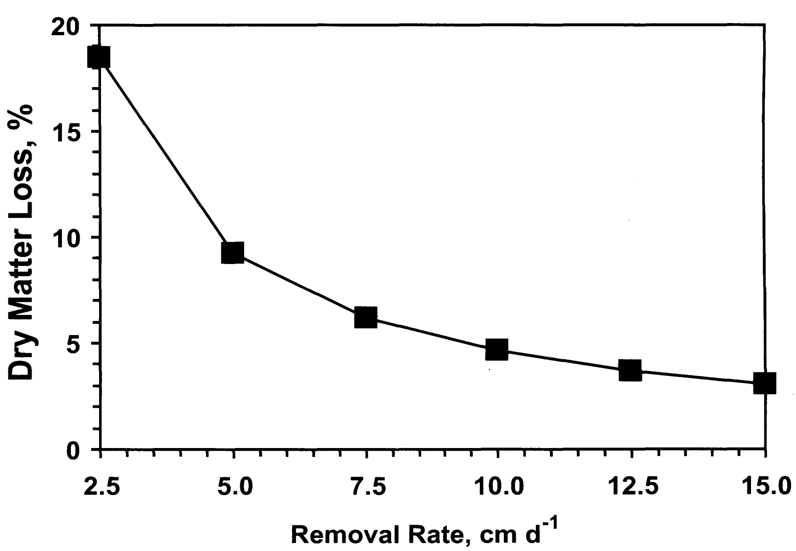

FIG. 40.12. Simulated DM loss during emptying as affected by removal rate from a bunker silo. A 350 g DM kg^{-1} corn silage at a density of 640 kg silage m^{-3} was assumed. (Adapted from Pitt and Muck, 1993.)

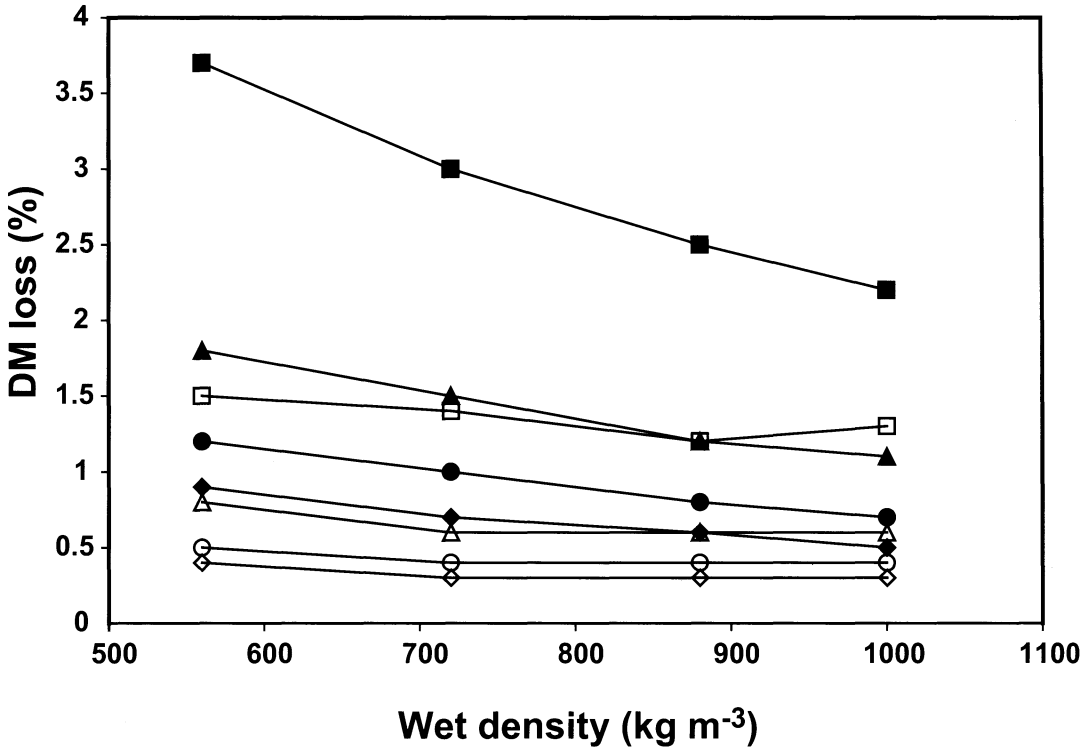

FIG. 40.13. Predicted 25-yr average difference in DM loss between silo unloaders (bucket minus milling type) as affected by silage density, unloading rate (cm d^{-1} = 5, *square*; 10, *triangle*; 15, *circle*; 20, *diamond*), and crop (alfalfa = *filled symbol*; corn = *open symbol*). (Adapted from Muck and Rotz, 1996.)

tion of long particles in alfalfa silage made it very difficult to make a smooth face with a bucket unloader. Extending those results, Muck and Rotz (1996) predicted that a milling device would provide modest but significant reductions in DM loss with a greater response for low-density silages or slow feedout rates (Fig 40.13).

Additives

Fermentation in the silo is often a loosely controlled process leading to less than optimal preservation of nutrients. Silage additives can be used to modify silage fermentation and/or aerobic stability during feedout. Some common reasons for using additives during the ensiling process are to

- Inhibit growth of aerobic microorganisms (especially those associated with aerobic instability, such as lactate-assimilating yeasts, and poor hygiene, such as *Listeria monocytogenes*).
- Inhibit growth of undesirable anaerobic organisms (e.g., enterobacteria and clostridia).
- Inhibit activity of plant and microbial proteases and deaminases.
- Improve the supply of fermentable substrates for LAB.
- Add beneficial microorganisms to dominate fermentation.
- Supply or release nutrients to stimulate growth of beneficial microorganisms.
- Alter ensiling conditions to optimize fermentation (e.g., absorbents).
- Form beneficial end products that stimulate animal intake and productivity.
- Improve nutrient and DM recovery.

Inoculants

Many bacteria, generally LAB, have been used as microbial inoculants to improve silage fermentation. Most species in silage inoculants (e.g., *Lactobacillus plantarum*, *Pediococcus* spp.) have been called homolactic LAB. Homolactic bacteria produce only lactic acid from glucose fermentation. This fermentation via the Embden-Meyerhof-Parnas pathway is desirable because it yields high recoveries of energy (99.3%) and DM (100%) and converts all of the glucose into lactic acid, a strong acid (McDonald et al., 1991). In contrast, heterolactic bacteria produce multiple end products including lactic acid, ethanol, acetic acid, and CO_2, because these organisms lack the enzyme fructose-diphosphate aldolase. Energy recoveries are still high (≥98%), but DM recoveries are reduced (≥76%). Today, however, many inoculant species have been reclassified as facultative heterolactics because when substrate availability is low, they increase energy extraction by producing multiple end products.

Some silage inoculants contain multiple strains of LAB to take advantage of potential synergistic actions. In general, populations of enterococci and pediococci grow faster than the lactobacilli when pH is high (>5.0) and oxygen is present. However, below pH 5.0, populations of *Enterococcus* species decrease sharply relative to species such as *L. plantarum* and *P. pentosaceus* (Bolsen et al., 1992b; Lin et al., 1992). Thus, *Enterococcus* species alone are generally unable to improve silage quality (Cai et al., 1999). Pediococci are also common inoculant species because of their tolerance of low moisture conditions.

When effective, inoculation with LAB results in a faster rate of fermentation, less proteolysis, more lactic acid, less acetic and butyric acids, less ethanol, a lower pH, and greater recovery of energy and DM. These benefits primarily come from the inoculant bacteria overwhelming the natural LAB, guaranteeing an efficient conversion of sugars to lactic acid. Less proteolysis results because clostridia, enterobacteria, and plant proteases are inhibited by rapid acidification. Inhibition of clostridia also reduces butyric acid production and concentration.

Beyond improving silage fermentation, LAB inoculants have also improved animal performance. Kung and Muck (1997) summarized reports indicating positive effects of inoculants on intake, gain, and milk production. Where milk production benefited, the average increase was 1.4 kg d^{-1} cow^{-1}. Summarizing their research results Bolsen et al. (1992a) reported that inoculants improved feed efficiency by 1.8%, and steers gained an additional 1.6 kg body weight Mg^{-1} crop ensiled. However, Satter et al. (1991) observed no benefit in animal production unless the inoculant increased numbers of LAB at ensiling by 10-fold. When this occurred, milk production averaged 2.5% higher in cows fed inoculated silage.

Miscellaneous Organisms

Homolactic LAB have not proven to be very successful in inhibiting microorganisms that cause aerobic spoilage. This lack of success has led to other species appearing in inoculants. For example, *Propionibacteria* are able to convert lactic acid and glucose to acetic and propionic acids that are more inhibitory to yeasts and molds than lactic acid. However, few published studies have shown improved aerobic stability from addition of these bacteria (Dawson et al., 1998; Flores-Galaraza et al., 1992), probably because *Propionibacteria* are strict anaerobes, grow slowly, and are relatively acid intolerant.

Recently, *Lactobacillus buchneri* has been marketed as an inoculant for improving the aerobic stability of silages. This organism converts lactic acid to acetic acid, 1,2-propanediol, and ethanol under anaerobic conditions when the pH is low (Elferink et al., 2001). Increased aerobic stability has been reported in a variety of silages (Driehuis et al., 2001; Kung and Ranjit, 2001; Kung et al., 2003; Muck, 2002) and appears to be primarily due to acetic acid. In some instances, silages treated with *L. buchneri* have had greater concentrations of propionic acid. This acid appears to be produced from diol-metabolizing lactobacilli rather than *L. buchneri* (Krooneman et al., 2002).

Enzymes

A variety of enzymes, particularly those breaking down plant fiber and starch, have been used as silage additives. Plant fiber–digesting enzymes (cellulases and hemicellulases) are the most widely used enzyme additives. Pectinases, cellobiase, amylases, and glucose oxidase are others that have been included in additives.

Fiber-digesting enzymes could provide additional substrate for fermentation by partially hydrolyzing plant cell walls (cellulose and hemicellulose) to produce soluble sugars. This would be particularly advantageous for perennial forages where pH might not otherwise be low enough to prevent clostridial activity. However, the rate of cellulose hydrolysis must be sufficiently fast to provide sugars while the LAB are still actively growing.

Partial digestion of the plant cell wall may also improve rate and/or extent of DM digestibility in the ruminant. For an improvement in digestibility, a change in the association of various cell wall components must occur.

Cell wall–degrading enzymes have been shown to hydrolyze cellulose and hemicellulose in trials (Muck and Kung, 1997). This has helped to lower pH where substrate limited fermentation. These enzymes have been less successful in terms of improving digestibility and animal performance than might be expected (Kung and Muck, 1997).

Nonprotein Nitrogen

Both ammonia and urea have been used as silage additives, particularly to improve corn silage quality. Ammonia has been applied as anhydrous ammonia or in mixtures with water or molasses. Ammonia additions have resulted in (a) addition of an economical source of crude protein (Huber et al., 1979); (b) reduced heating and spoilage during storage and feeding (Britt and Huber, 1975); and (c) decreased protein degradation in the silo (Johnson et al., 1982). Urea has also been added to corn silage (5–6 kg Mg^{-1}) as an economical source of crude protein. However, beneficial effects of urea on aerobic stability and proteolysis have not been well substantiated. Whenever ammonia or urea is added to the diet, special attention should be made to ensure that degradable and undegradable protein requirements are balanced for the target ruminant animal.

Application of anhydrous ammonia should be at 8–10 kg N Mg^{-1} forage DM. This will increase the crude protein concentration in corn silage by 50–60 g kg^{-1} DM. Excess ammonia (14–18 kg N Mg^{-1} DM) may result in poor fermentation (because of a prolonged buffering effect), and both the poor fermentation and high ammonia concentrations can reduce animal performance. The Cold-flo method is the simplest way to apply ammonia. Gaseous ammonia is supercooled in a converter box and about 80%–85% becomes liquid.

Anhydrous ammonia should not be added to corn forage below 580–600 g moisture kg^{-1} because fermentation is restricted in drier material and binding of ammonia to the forage is poorer. If forage moisture is below this level, water–ammonia or molasses–ammonia mixes should be used. Rates and application methodology for molasses–ammonia mixes should be as recommended by the manufacturer.

Acids

Many acids have been added to forages at ensiling to alter silage fermentation. Much research has been conducted in Europe using formic acid as a silage additive, and it has been a popular means to avoid clostridial activity in unwilted cool-season grass silages. Formic acid immediately reduces pH to 4.7–4.8 and allows natural fermentation to decrease pH further.

However, in the United States, the use of acids other than propionic acid is uncommon. Propionic acid inhibits growth of yeasts and molds, improving aerobic stability. Undissociated propionic acid has good antifungal properties, and the fraction of propionic acid left undissociated depends on pH (Lambert and Stratford, 1999). At the pH of standing crops, 6.5, only about 1% of the acid is in the undissociated form whereas at a pH of 4.8 about 50% of the acid is undissociated. The undissociated acid functions both by staying active on the surface of microorganisms, competing with amino acids for space on active sites of enzymes, and by altering the cell permeability of microorganisms.

Like other acids, propionic acid is corrosive. Thus, the acid salts (e.g., calcium, sodium, and ammonium propionate) have been used in some commercial products to form a "buffered" acid. The antifungal properties of propionic acid and its salts parallel their solubility in water. Among these salts, ammonium propionate is most soluble in water (90%), followed by sodium propionate (25%) and calcium propionate (5%).

Currently, in the United States, there are many buffered propionic acid products with relatively low suggested application rates (0.5–2.0 g kg^{-1} fresh weight). Often other antimycotic agents (e.g., sorbic, benzoic, citric, and acetic acids) are added. In several experiments with such additives, application rates of 2–3 g kg^{-1} were needed to consistently improve aerobic stability of corn silage (Kung et al., 2000; Kung et al., 1998).

Troubleshooting

Effluent

In many areas, unfavorable conditions make wilting of forage crops difficult or impossible. Crops with high moisture (>700 g kg^{-1}) can have large nutrient losses from poor fermentation and excessive production of effluent. This effluent is also a potential contaminant to waterways because of its high nutrient content.

Two primary approaches are used to control this problem: (1) collection and land spreading and (2) mixing absorbents with forages to decrease moisture concentration and reduce effluent. Cereal straw (Offer and Alrwidah, 1989), alfalfa cubes (Fransen and Strubi, 1998), cereal grains (Jones et al., 1990), and beet pulp (Ferris and Mayne, 1994) have been used for this purpose. Jones and Jones (1996) concluded that the use of high-fiber material (e.g., straw and paper) to reduce silage effluent had little practical value because it reduced the nutritive value of silage. Inclusion of cereal grains was not always successful, and practical difficulties such as the need to preroll or grind discouraged this practice. Inclusion of sugar beet pulp was chosen as a good alternative. Overall, successful addition of absorbents is difficult, requiring increased labor at ensiling and uniform distribution throughout the silage mass.

Silo Gas

Various forms of nitrogen oxide are formed during fermentation, primarily by enterobacteria using nitrate as an electron acceptor in place of oxygen. These nitrogen oxides are collectively referred to as silo gas. Inhalation of even small quantities of nitrogen dioxide (NO_2) and nitrogen tetraoxide (NO_2O_4) can lead to chronic pulmonary problems and be fatal. Formation of silo gas occurs within 4–6 h of silo filling and may continue for a 2- to 3-wk period. During this time special care should be taken around fermenting feeds to avoid inhalation by humans, livestock, and pets. Along with CO_2, the nitrogen oxide gases are heavy and tend to settle in low areas. Some gases smell like bleach, but others are odorless. Some gases may also be yellow or brownish, whereas others are colorless. Yellow or reddish brown staining of equipment or silage may sometimes be observed.

To avoid silo gas, stay away from silos for at least 3 wk or more after filling. Ventilate upright silos before entering, and use a chemical detector to ensure safety.

Never enter an enclosed silo without having another person nearby.

Animal Performance

Numerous studies have investigated potential correlations between end products of silage fermentation and ruminant productivity. Conflicting evidence suggests that diets high in moisture from fermented feeds may decrease DM intake. The 1989 National Research Council (NRC) requirements for dairy cattle (National Research Council, 1989) reported that DM intake declines by 0.02% of body weight for each 10 g kg^{-1} increase in ration moisture above 500 g kg^{-1}. However, in a review of 392 lactating cow diets, Holter and Urban (1992) found no relationship between DM intake and ration moisture when moisture was greater than 500 g kg^{-1}. Similarly, although Rook and Gill (1990) reported moderately strong negative correlations between intake and acetic, butyric and total volatile fatty acids, Steen et al. (1998) reported only very weak correlations between these variables. Some silages also contain biogenic amines, and these compounds have sometimes been implicated in poor animal production.

The end products of clostridial fermentations may also have negative effects on animal performance and health. Because clostridial silages are often high in free amino acids and ammonia, excessive consumption of these end products can lead to asynchrony of optimal ruminal fermentation because of excessive amounts of rapidly available ammonia N. High levels of butyric acid in silage may also contribute to problems of cows in early lactation that are in negative energy balance as butyric acid is converted in the rumen wall to beta hydroxy butyrate, a ketone body. High levels of ketones in blood can lead to the metabolic disease state known as ketosis. Garrett Oetzel (Univ. of Wisconsin, personal communication, 2003) suggested limiting the intake of butyric acid by dairy cows to less than 50 g d^{-1} in order to avoid metabolic problems. Transition cows should receive no butyric acid in their rations.

Silages that are aerobically unstable heat and spoil primarily because yeasts assimilate lactic acid. Incorporating spoiled silage from the top layer of a bunker silo into steer diets markedly reduced DM intake, nutrient digestion, and adjusted daily gain (Whitlock, 1999). Feeding hot, spoiling feeds has been implicated as the reason for poor intake and milk production on many dairy farms. Surprisingly, there is no "rule of thumb" for describing the degree of spoilage required to cause decreases in animal performance.

Silages sometimes contain mycotoxins that can be extremely toxic to animals and humans (Scudamore and Livesey, 1998; Whitlow and Hagler, 2002). Mycotoxins have been suggested as causes of abortions, reduced intake, poor reproduction, and low milk production. Mycotoxins may be on the crop at ensiling, but their production and control in silage are not well understood. General recommendations for limiting their occurrence include minimizing plant disease (e.g., damage to the corn ear or stalk), rapid filling and tight packing of silos, and using silage preservatives designed to inhibit the growth of molds. Obtaining representative samples of forage from large silos for analyses of mycotoxins presents a challenge because they are usually not uniformly distributed throughout the silo.

Overall, silages that contain undesirable levels of fungal metabolites should be completely removed from the diet of lactating cows or minimized at the very least. Specifically, in the case of silages with mycotoxins, use of binders may be useful. However, to date, no products have been approved by the FDA for treatment of mycotoxicosis.

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